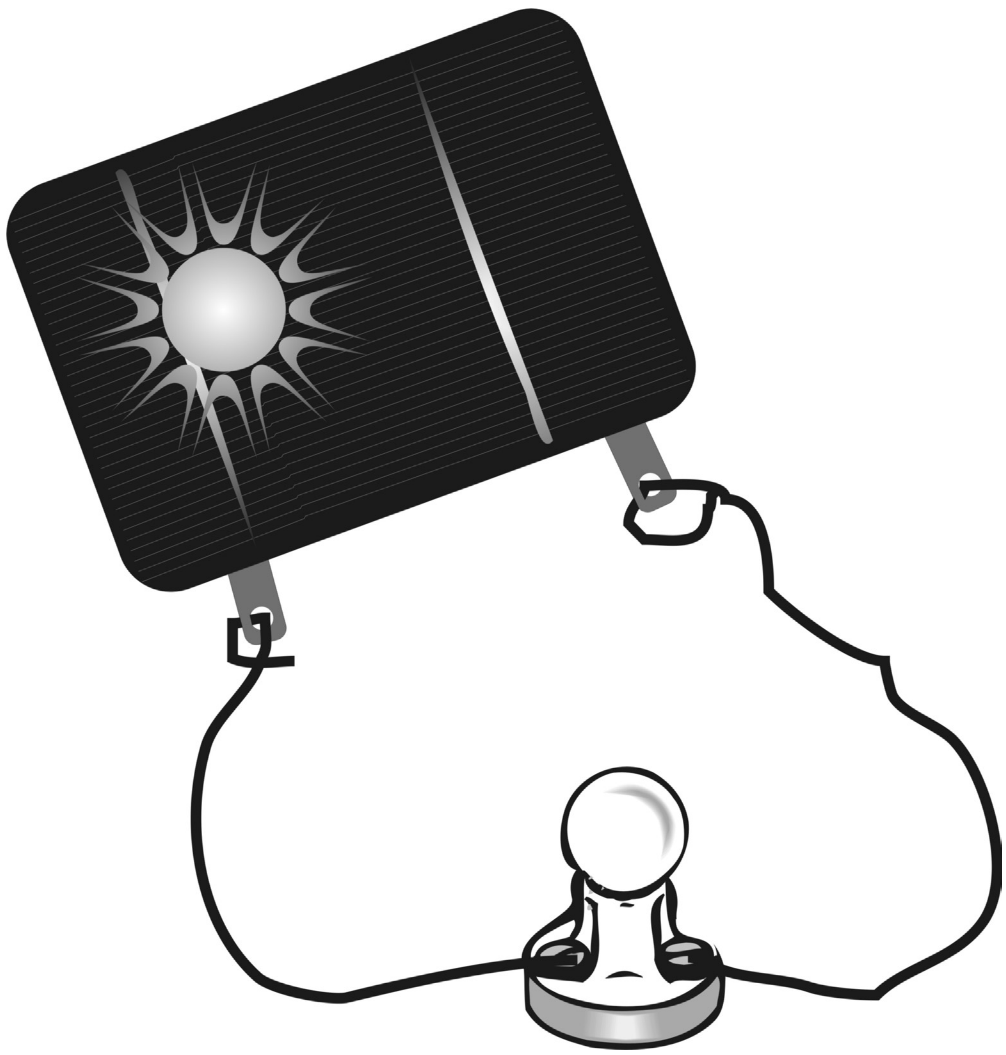
PHOTOVOLTAICS
Student Guide



NEED

2009-2010

Putting Energy into Education

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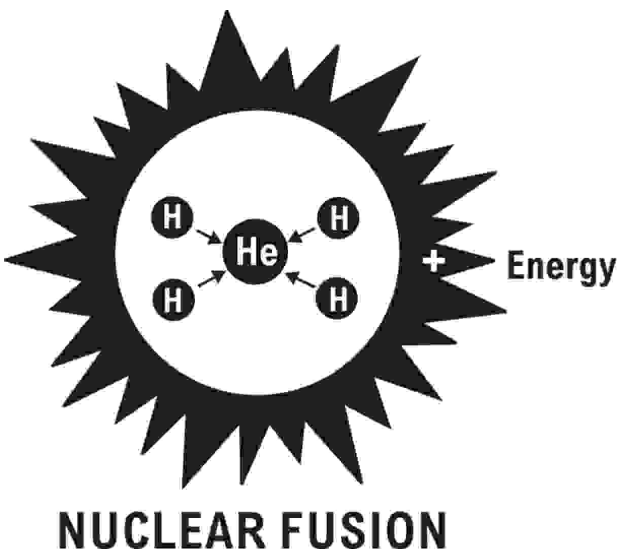
What Is Solar Energy?

Solar energy is radiant energy from the sun. It is vital to us because it provides the world—directly or indirectly—with almost all of its energy. In addition to providing the energy that sustains the world, solar energy is stored in fossil fuels and biomass, and is responsible for powering the water cycle and producing wind.

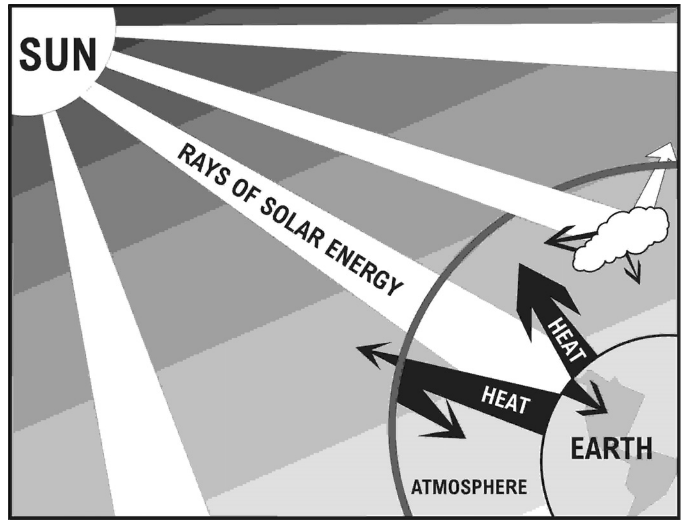
Every day the sun radiates, or sends out, an enormous amount of energy. The sun radiates more energy in one second than people have used since the beginning of time! Solar energy comes from within the sun itself. Like other stars, the sun is a big ball of gases – mostly hydrogen and helium. The hydrogen atoms in the sun's core combine to form helium and radiant energy in a process called **nuclear fusion**.



During nuclear fusion, the sun's extremely high pressure and temperature cause hydrogen atoms to come apart and their nuclei (the central cores of the atoms) to fuse or combine. Four hydrogen nuclei fuse to become one helium atom. But the helium atom contains less mass than the four hydrogen atoms that fused. Some matter is lost during nuclear fusion. The lost matter is emitted into space as **radiant energy**.

It takes millions of years for the energy in the sun's core to make its way to the solar surface, and then just a little over eight minutes to travel the 93 million miles to earth. The solar energy travels to the earth at a speed of 186,000 miles per second (3.0×10^8 meters per second), the speed of light. No heat from the sun travels to the earth; the light turns into heat when it is absorbed by molecules on or near earth.

Only a small portion of the energy radiated by the sun into space strikes the earth—one part in two billion. Yet this amount of energy is enormous. Every day enough energy strikes the United States to supply the nation's energy needs for one and a half years!



Where does all this energy go? About 15 percent of the sun's energy that hits the earth is reflected back into space. Another 30 percent powers the water cycle: it evaporates water that is then drawn into the atmosphere, turns into clouds, condenses, and falls back to earth as precipitation. Plants, the land, and the oceans also absorb solar energy. The rest could be used to supply our energy needs.

Solar energy is considered a **renewable** energy source. Renewable sources of energy are resources that are continually renewed by nature, and hence will never run out. Solar power is considered renewable because the nuclear (fusion) reactions that power the sun are expected to keep generating sunlight for many billions of years.

History of Solar Energy

People have harnessed solar energy for centuries. As early as the 7th century B.C., people used simple magnifying glasses to concentrate the light of the sun into beams so hot they could cause wood to catch fire.

More than 100 years ago in France, a scientist used heat from a solar collector to make steam to drive a steam engine. In the 1860s in the United States, John Ericsson developed the first realistic application of solar energy using a solar reflector to drive an engine in a steam boiler.

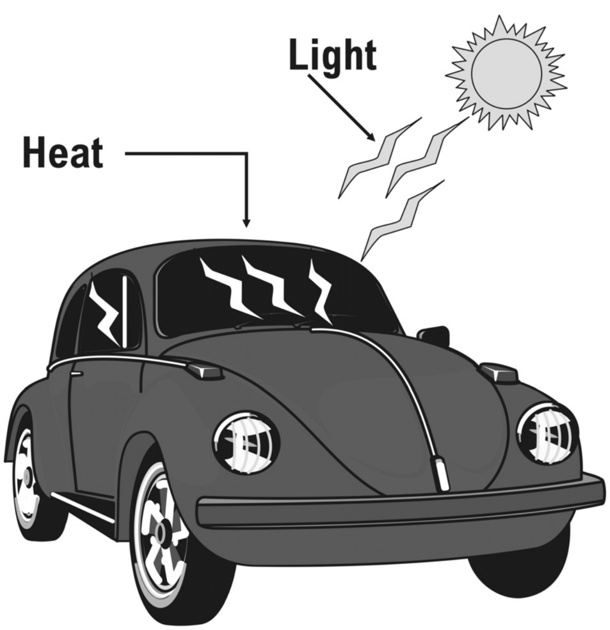
Early in the 1900s, scientists and engineers began seriously researching ways to use solar energy. The solar water heater gained popularity during this time in Florida, California, and the Southwest. The industry was in full swing just before World War II. This growth lasted until the mid-1950s when low-cost natural gas became the primary fuel for heating homes and water, and solar heating lost popularity.

The public and world governments remained largely indifferent to the possibilities of solar energy until the energy crises of the 1970s. Research efforts in the U.S. and around the world since that time have resulted in tremendous improvements in solar technologies for heating water and buildings and making electricity.

Solar Collectors

Heating with solar energy is relatively easy—just look at a car parked in the sun with its windows closed. Getting the right amount of heat in a desired location, however, requires more thought and careful design. Capturing sunlight and putting it to work effectively is difficult because the solar energy that reaches the earth is spread out over a large area. The sun does not deliver that much energy to any one place at any one time.

How much solar energy a place receives depends on several conditions. These include the time of day, the season of the year, the latitude of the area, and the clearness or cloudiness of the sky.



On a sunny day, a closed car works as a solar collector. Light passes through the glass, is absorbed and changed into heat. The heat then gets trapped inside.

A solar collector is one way to collect heat from the sun. A closed car on a sunny day is like a solar collector. As the sunlight passes through the car's glass windows, it is absorbed by the seat covers, walls, and floor of the car.

The light that is absorbed changes into heat. The car's glass windows let light in, but don't let all the heat out. This is also how greenhouses are deisgned to stay warm year-round. A greenhouse or solar collector:

- allows sunlight in through the glass;
- absorbs the sunlight and changes it into heat; and
- traps most of the heat inside.

Solar Space Heating

Space heating means heating the space inside a building. Today many homes use solar energy for space heating. There are two general types of solar space heating systems: passive and active.

Passive Solar Homes

In a passive solar home, the house itself operates as a solar collector. A passive house does not use any special mechanical equipment such as pipes, ducts, fans, or pumps to transfer the heat that the house collects on sunny days. Instead, a passive solar home relies on properly oriented windows and is designed with added thermal mass to store and release heat. Since the sun shines from the south in North America, passive solar homes are built so that most of the windows face south. They often have few or no windows on the north side.

A passive solar home converts solar energy into heat just as a closed car does. Sunlight passes through a home's windows and is absorbed in the walls and floors. Materials such as tile, stone and concrete are often used, because they can store more heat than wood or sheetrock. To control the amount of heat in a passive solar house, the designer must determine the appropriate balance of mass in the floors and walls with the admission of sunlight.

Windows let in the sunlight, which is converted into heat when it is absorbed by the walls and floors. The mass stores the heat from the sun and releases it when the air temperature inside drops below the temperature of the mass. Heating a house by warming the walls or floors is more comfortable than heating the air inside a house.

Additionally, the doors and windows can be closed to keep heated air in or opened to let it out to keep the temperature in a comfortable range. At night, special heavy curtains or shades can be pulled over the windows to keep the daytime heat inside the house. In the summer, awnings or roof overhangs help to shade the windows from the high summer sun to prevent the house from overheating. Passive homes are quiet, peaceful places to live. A well-designed passive solar home can harness 50 to 80 percent of the heat it needs from the sun.

Many passive homeowners install equipment such as fans to help circulate air to further increase the comfort and energy efficiency of their homes. When special equipment is added to a passive solar home, it is called a **hybrid** system.

Active Solar Homes

Unlike a passive solar home, an active solar home uses mechanical equipment such as pumps and blowers to gain greater control of when, where and how much of the collected heat from the sun gets used. The active solar home is designed to deliver the heat from where it is collected to where it is needed.

Storing Solar Heat

The challenge confronting any solar heating system—whether passive, active, or hybrid—is heat storage. Solar heating systems must have some way to store the heat that is collected on sunny days to keep people warm at night or on cloudy days.

In passive solar homes, heat is stored by using dense interior materials that retain heat well—masonry, adobe, concrete, stone, or water. These materials absorb surplus heat and radiate it back into the room when the air temperature is lower than the surface temperature of the material. Some passive homes have walls a foot thick.

In active solar homes, heat may be stored in one of two ways—a large tank may store a heated liquid, or rock bins beneath the house may store warm mass. Houses with active or passive solar heating systems may also have furnaces, wood-burning stoves, or other heat sources to provide heat during long periods of cold or cloudy weather. These are called **backup** systems.

Solar Water Heating

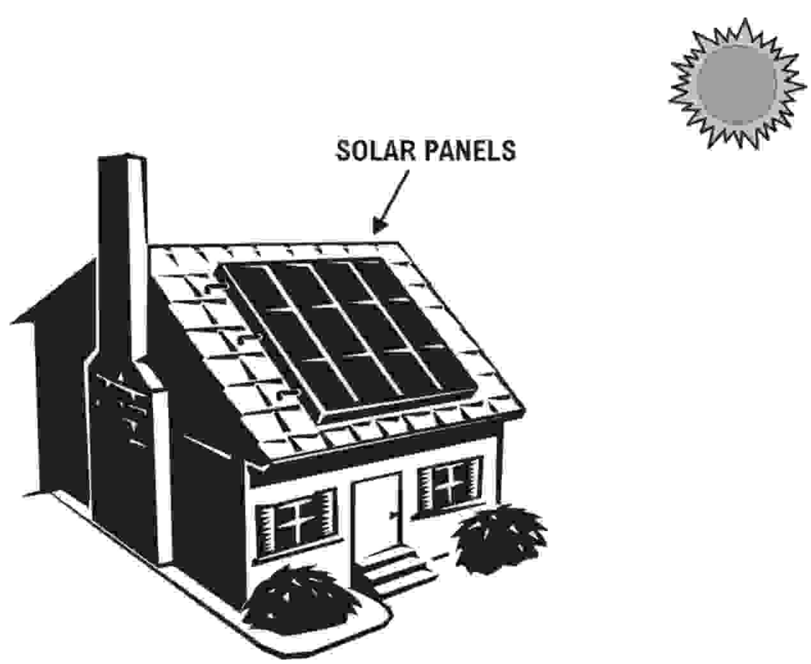
Solar energy is also used to heat water. Water heating is usually the second leading home energy expense, costing the average family over $400 a year.

Depending on where you live, and how much hot water your family uses, a solar water heater can pay for itself in as little as five years. A well-maintained solar water heating system can last 15-20 years, longer than a conventional water heater.

A solar water heater works in the same way as solar space heating. A solar collector is mounted on the roof, or in an area of direct sunlight. It collects sunlight and converts it to heat. When the fluid in the system becomes hot enough, a thermostat starts a pump. The pump circulates the fluid through the collector until it reaches the required temperature, called the **set point**. Then the heated fluid is pumped to a storage tank where it is used in a **heat exchanger** to heat water.

The hot water may then be piped to a faucet or showerhead. Most solar water heaters that operate in cold climates use a heat transfer fluid similar to antifreeze that will not freeze and damage the system.

Today, over 1.5 million homes in the U.S. use solar heaters to heat water for their homes or swimming pools. Besides heating homes and water, solar energy also can be used to produce electricity. Two ways to generate electricity from solar energy are photovoltaics and solar thermal systems.



Photovoltaics

Alessandro Volta

Photovoltaic (or PV) systems convert light directly into electricity. The term *photo* comes from the Greek *phos*, which means light. The term *volt* is a measure of electricity named for Alessandro Volta (1745-1827), a pioneer in the development of electricity. Photovoltaics literally means *light–electricity*.

Commonly known as solar cells, PV cells are already an important part of our lives. The simplest PV systems power many of the small calculators and wrist watches we use every day. Larger PV systems provide electricity for pumping water, powering communications equipment, and even lighting homes and running appliances.

In certain applications, such as motorist aid call boxes on highways and pumping water for livestock, PV power is the cheapest form of electricity. Some electric utility companies are building PV systems into their power supply networks.

History of Photovoltaics

French physicist Edmond Becquerel first described the photovoltaic (PV) effect in 1839, but it remained a curiosity of science for the next half century. At the age of 19, Becquerel found that certain materials would produce small amounts of electric current when exposed to light. The effect was first studied in solids, such as selenium, by Heinrich Hertz in the 1870s. Soon selenium PV cells were converting light to electricity at one to two percent efficiency.

The **conversion efficiency** of a PV cell is the proportion of radiant energy that the cell converts into electrical energy relative to the amount of radiant energy that is available and striking the PV cell. This is very important when discussing PV devices, because improving this efficiency is vital to making PV energy competitive with more traditional sources of energy, such as fossil fuels.

During the second half of the 20th century, PV science was refined and the process more fully explained. Major steps toward commercializing PV were taken in the 1940s and 1950s, when the Czochralski process was developed for producing highly pure crystalline silicon.

In 1954, scientists at Bell Laboratories depended on the Czochralski process to develop the first crystalline silicon photovoltaic cell, which had a conversion efficiency of four percent.

As a result of technological advances, the cost of PV cells has decreased significantly over the past 25 years, as the efficiency has increased. Today's commercially available PV devices convert seven to 17 percent of the radiant energy that strikes them into electricity.

In the laboratory, combining exotic materials with specialized cell designs has produced PV cells with conversion efficiencies as high as 38 percent.

Solar Systems

The **photovoltaic effect** is the basic physical process through which a PV cell converts sunlight directly into electricity. PV technology works any time the sun is shining, but more electricity is produced when the light is more intense and when it is striking the PV modules directly—when the rays of sunlight are perpendicular to the PV modules.

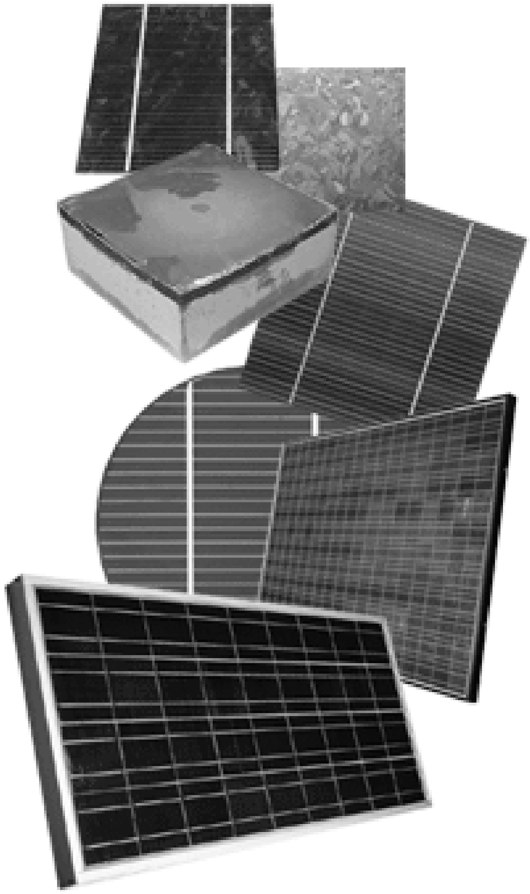
Unlike solar systems for heating water, with which you might be more familiar, PV technology does not produce heat to make electricity. Instead, PV cells generate electricity directly from the electrons freed by the interaction of radiant energy with the semi-conductor materials in the PV cells.

Sunlight is composed of **photons**, or bundles of radiant energy. When photons strike a PV cell, they may be reflected or absorbed, or transmitted through the cell.

Only the absorbed photons generate electricity. When the photons are absorbed, the energy of the photons is transferred to electrons in the atoms of the solar cell, which is actually a semi-conductor.

With their newfound energy, the electrons are able to escape from their normal positions associated with their atoms to become part of the current in an electrical circuit. By leaving their positions, the electrons cause holes to form in the atomic structure of the cell into which other electrons can move.

Special electrical properties of the PV cell—a built-in electric field—provide the voltage needed to drive the current through a circuit and power an external load, such as a light bulb.



Different materials are used to produce PV cells, but silicon—the main ingredient in sand—is the most common basic material. Silicon is a relatively cheap material because it is widely available and used in other things, such as televisions, radios and computers. PV cells, however, require very pure silicon, which can be expensive to produce.

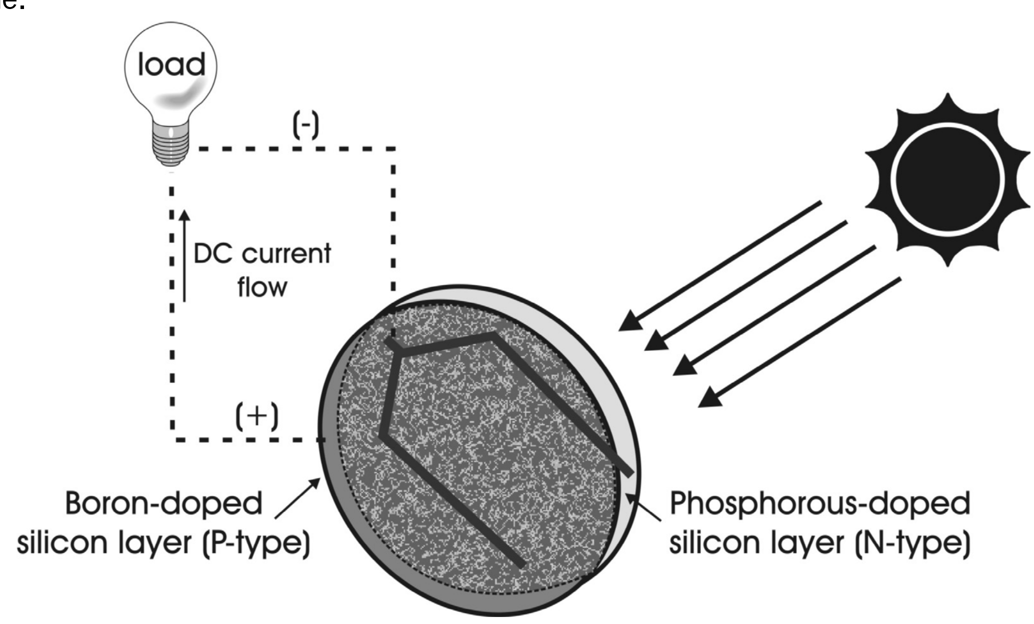
The amount of electricity a PV cell produces depends on its size, its conversion efficiency and the intensity of the light source. Efficiency is a measure of the amount of electricity produced from the sunlight that a cell receives. A typical PV cell produces 0.5 volts of electricity. It takes just a few PV cells to produce enough electricity to power a small watch or solar calculator.

The most important parts of a PV cell are the semi-conductor layers, where the electric current is created. There are a number of different materials suitable for making these semi-conducting layers, and each has benefits and drawbacks. Unfortunately, there is no one ideal material for all types of cells and applications.

When sunlight strikes the surface of a PV cell, the electrical field provides momentum and direction to the light-stimulated electrons, resulting in a flow of electric current, or flow of electrons, when the solar cell is connected in a circuit.

Photovoltaic Cells

The basic building block of PV technology is the photovoltaic cell. PV cells come in many shapes and sizes. The most common shapes are circles, rectangles and squares. The size and the shape of a PV cell and the number of PV cells required for one PV module depend on the material of which the PV cell is made.



How a PV Cell is Made

Let's look more closely at how a PV cell is made and how it produces electricity.

Step 1

A slab (or wafer) of pure silicon is used to make a PV cell. The top of the slab is very thinly diffused with an "n" dopant such as phosphorous. On the base of the slab a small amount of a "p" dopant, typically boron, is diffused. The boron side of the slab is 1,000 times thicker than the phosphorous side. Dopants are similar in atomic structure to the primary material. The phosphorous has one more electron in its outer shell than silicon, and the boron has one less. These dopants help create the electric field that motivate the energetic electrons out of the cell created when light strikes the PV cell.

The phosphorous gives the wafer of silicon an excess of free electrons; it has a negative character. This is called the n-type silicon. The n-type silicon is not charged – it has an equal number of protons and electrons – but some of the electrons are not held tightly to the atoms. They are free to move to different locations within the layer.

The boron gives the base of the silicon a positive character, because it has a tendency to attract electrons. The base of the silicon is called p-type silicon (p = positive). The p-type silicon has an equal number of protons and electrons; it has a positive character but not a positive charge.

Step 2

Where the n-type silicon and p-type silicon meet, free electrons from the n-layer flow into the p-layer for a split second, then form a barrier to prevent more electrons from moving between the two sides. This point of contact and barrier is called the p-n junction.

When both sides of the silicon slab are doped, there is a negative charge in the p-type section of the junction and a positive charge in the n-type section of the junction due to movement of the electrons and "holes" in at the junction of the two types of materials. This imbalance in electrical charge at the p-n junction produces an electric field between the p-type and n-type.

Step 3

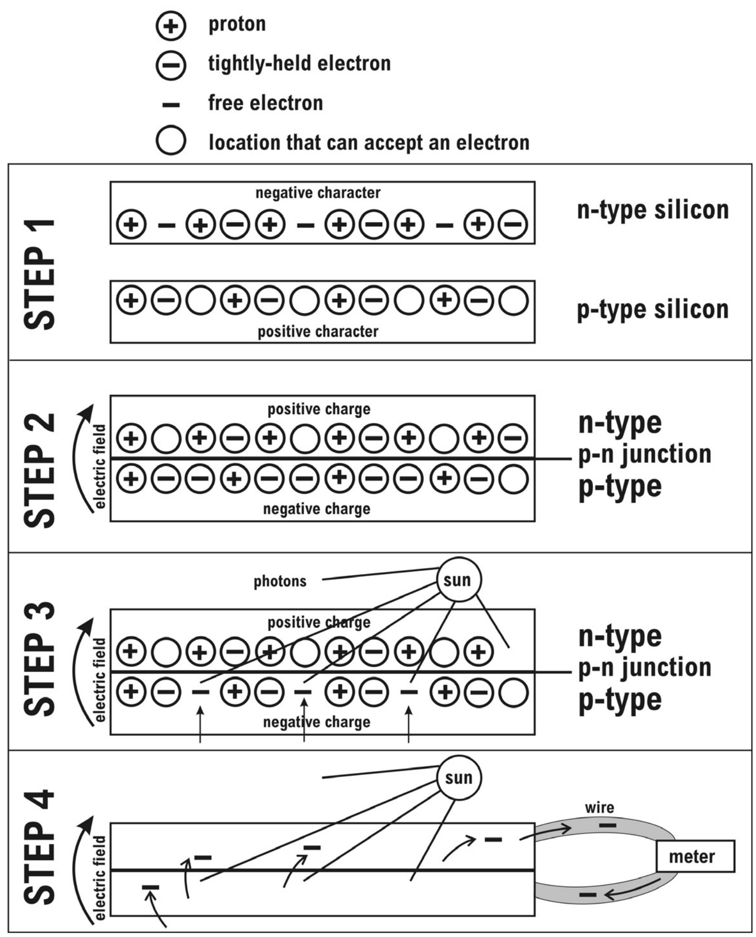
If the PV cell is placed in the sun, photons of light strike the electrons in the p-n junction and energize them, knocking them free of their atoms. These electrons are attracted to the positive charge in the n-layer and repelled by the negative charge in the p-layer. Most photon-electron collisions actually occur in the silicon base.

Step 4

A conducting wire connects the p-type layer to electrical application such as a light or battery, and then back to the n-type layer, forming a complete circuit. As the free electrons are pushed into the n-type silicon they repel each other because they are of like charge. The wire provides a path for the electrons to move away from each other. This flow of electrons is an electric current that can power a load, such as a calculator or other device, as it travels through the circuit from the n-layer to the p-layer.

In addition to the semi-conducting materials, solar cells consist of a top metallic grid or other electrical contact to collect electrons from the semi-conductor and transfer them to the external load, and a back contact layer to complete the electrical circuit.

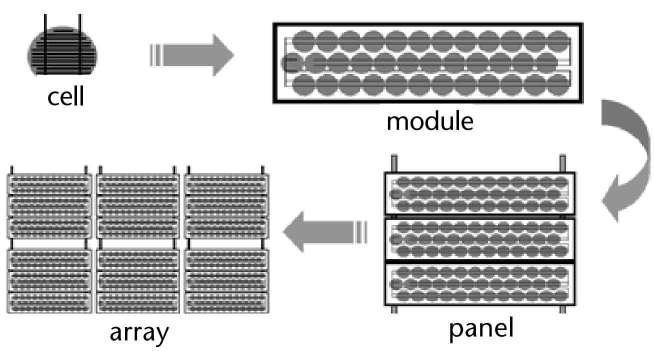
PHOTOVOLTAIC CELL



PV Modules, Panels and Arrays

For more power, cells are connected together to form larger units called **modules**. Photovoltaic cells are connected in series and/or parallel circuits to produce higher voltages, currents and power levels. A PV module is the smallest PV component sold commercially, and can range in power output from about 10 watts to 300 watts.

A typical PV module consists of PV cells sandwiched between a clear front sheet, usually glass, and a backing sheet, usually glass or a type of tough plastic. This protects them from breakage and from the weather. An aluminum frame can be fitted around the PV module to enable easy affixing to a support structure. Photovoltaic **panels** include one or more PV modules assembled as a pre-wired, field-installable unit. A PV **array** is the complete power-generating unit, consisting of any number of modules and panels.



PV System Components

Although a PV module produces power when exposed to sunlight, a number of other components are required to properly conduct, control, convert, distribute, and store the energy produced by the array. Depending on the type of system, these components may include:

Power Inverter: PV modules, because of their electrical properties, produce direct current (DC) rather than alternating current (AC). Direct current is electric current that flows in a single direction. Many simple devices, such as those that run on batteries, use direct current. Alternating current, in contrast, is electric current that reverses its direction of flow at regular intervals (120 times per second). This is the type of electricity provided by utilities and the type required to run most modern appliances and electronic devices.

In the simplest systems, DC current produced by PV modules is used directly. In applications where AC current is necessary, an **inverter** can be added to the system to convert DC to AC current.

Battery System: PV systems cannot store electricity, so batteries are often added. A PV system with a battery is configured by connecting the PV array to an inverter. The inverter is connected to a battery bank and to any load. During daylight hours, the PV array charges the battery bank. The battery bank supplies power to the load whenever it is needed. A device called a charge controller keeps the battery properly charged and prolongs its life by protecting it from being overcharged and completely discharged.

PV systems with batteries can be designed to power DC or AC equipment. Systems operating only DC equipment do not need an inverter, only a charge controller.

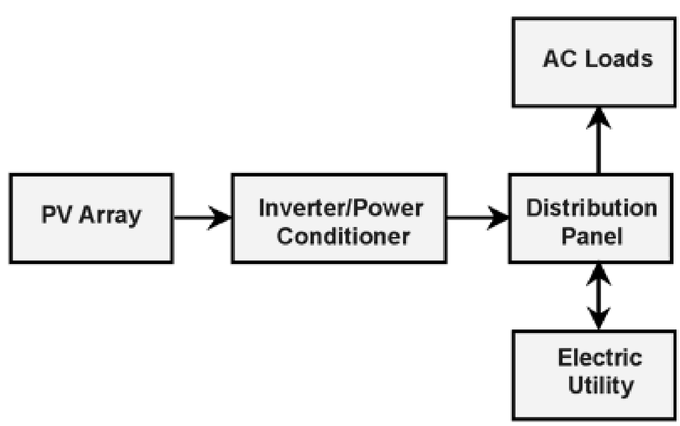
PV Systems

Two types of PV systems are grid-connected systems and stand-alone systems. The main difference between these systems is that one is connected to the utility grid and the other is not.

Grid Connected Systems

Grid-connected PV systems are designed to operate in parallel with and interconnected with the national electric utility grid. What is the **grid**? It is the network of cables through which electricity is transported from power stations to homes, schools and other places. A grid connected PV system is linked to this network of power lines.

The primary component of a grid-connected PV system is the inverter, or **power conditioning unit (PCU)**. The inverter converts the DC power produced by the PV system into AC power consistent with the voltage and power quality requirements of the utility



grid.

This means that it can deliver the electricity it produces into the electricity network and draw it down when needed; therefore, no battery or other storage is needed.

Stand-alone Systems

As its name suggests, this type of PV system is a separate electricity supply system. A **stand-alone system** is designed to operate independent of the electric utility grid and to supply electricity to a single system. Usually a stand-alone system includes one or more batteries to store the electricity.

Historically, PV systems were used only as stand–alone systems in remote areas where there was no other electricity supply. Today, stand-alone systems are used for water pumping, highway lighting, weather stations, remote homes and other uses away from power lines.

Benefits and Limitations

Benefits

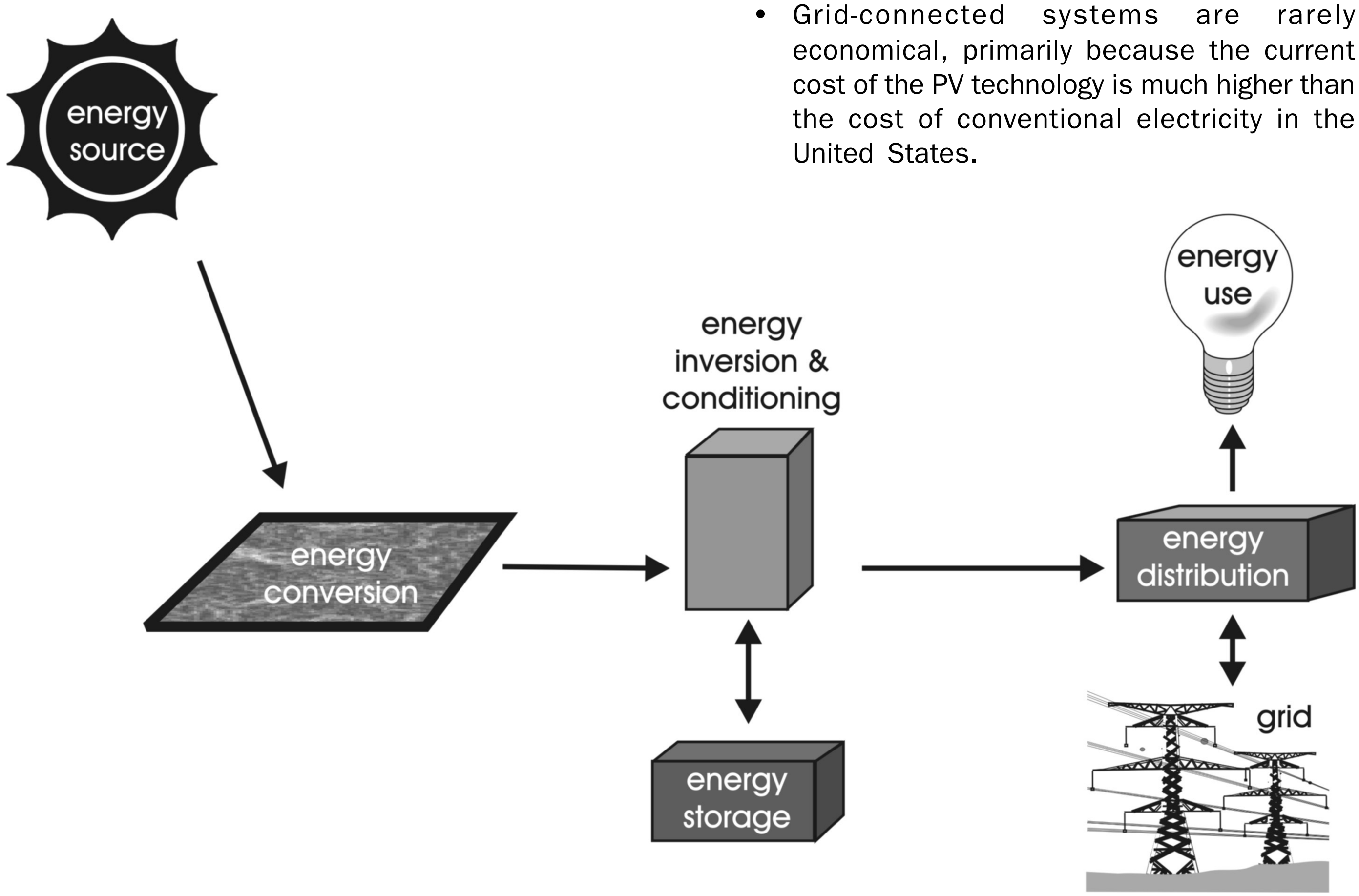
Solar electric systems offer many advantages:

- They are safe, clean and quiet to operate.
- They are highly reliable.
- They require virtually no maintenance.
- They are cost-effective in remote areas and for some residential and commercial applications.
- They are flexible and can be expanded to meet increasing electrical needs.
- They can provide independence from the grid or backup during outages.
- The fuel is renewable and free.

Limitations

There are also several practical limitations to PV systems:

- PV systems are not well suited for energy-intensive uses such as heating.
- Grid-connected systems are rarely economical, primarily because the current cost of the PV technology is much higher than the cost of conventional electricity in the United States.



Measuring Electricity

Electricity makes our lives easier, but it can seem like a mysterious force. Measuring electricity is confusing because we cannot see it. We are familiar with terms such as watt, volt, and amp, but we do not have a clear understanding of these terms. We buy a 60-watt lightbulb, a tool that needs 120 volts, or a vacuum cleaner that uses 8.8 amps, and don't think about what those units mean.

Using the flow of water as an analogy can make electricity easier to understand. The flow of electrons in a circuit is similar to water flowing through a hose. If you could look into a hose at a given point, you would see a certain amount of water passing that point each second.

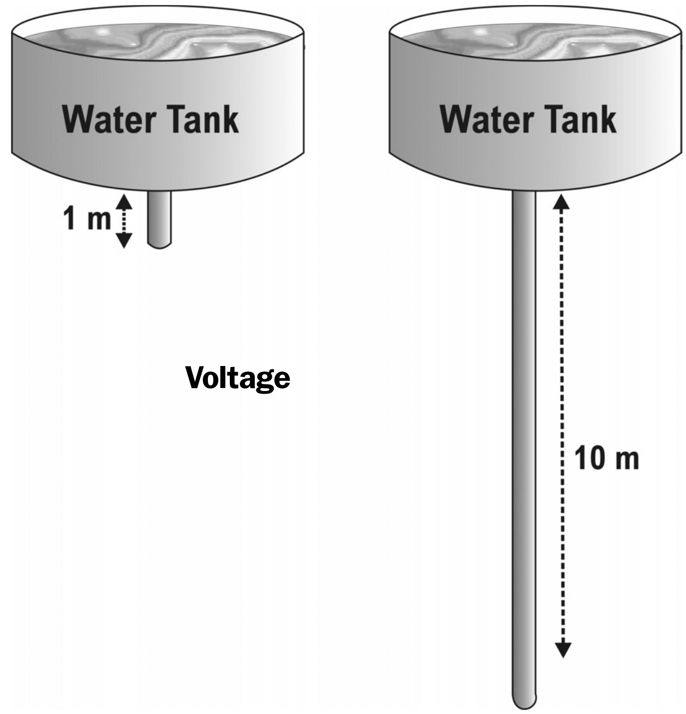
The amount of water depends on how much pressure is being applied––how hard the water is being pushed. It also depends on the diameter of the hose. The harder the pressure and the larger the diameter of the hose, the more water passes each second. The flow of electrons through a wire depends on the electrical pressure pushing the electrons and on the cross-sectional area of the wire.

Voltage

The pressure that pushes electrons in a circuit is called **voltage**. Using the water analogy, if a tank of water were suspended one meter above the ground with a ten-centimeter pipe coming out of the bottom, the water pressure would be similar to the force of a shower. If the same water tank were suspended 10 meters above the ground, the force of the water would be much greater, possibly enough to hurt you.

Voltage (V) is a measure of the pressure applied to electrons to make them move. It is a measure of the strength of the current in a circuit and is measured in **volts (V)**. Just as the 10-meter tank applies greater pressure than the 1-meter tank, a 10-volt power supply (such as a battery) would apply greater pressure than a 1-volt power supply.

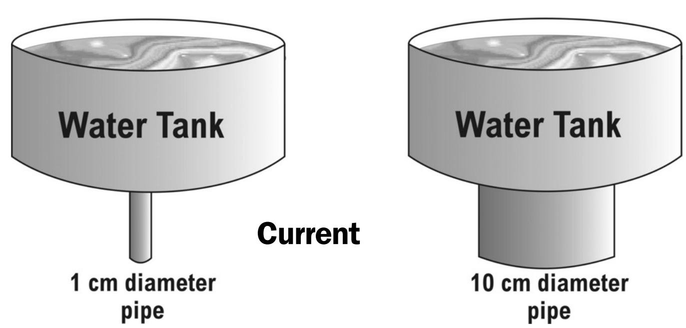
AA batteries are 1.5-volt; they apply a small amount of voltage or pressure for lighting small flashlight bulbs. A car usually has a 12-volt battery—it applies more voltage to push current through circuits to operate the radio or defroster. The voltage of typical wall outlets is 120 volts—a dangerous amount of voltage. An electric clothes dryer is usually wired at 240 volts—a very dangerous voltage.



Current

The flow of electrons can be compared to the flow of water. The water current is the number of molecules flowing past a fixed point; electrical current is the number of electrons flowing past a fixed point. **Electrical current (I)** is defined as electrons flowing between two points having a difference in voltage. Current is measured in **amperes** or **amps (A)**. One ampere is 6.25×10^{18} electrons per second passing through a circuit.

With water, as the diameter of the pipe increases, so does the amount of water that can flow through it. With electricity, conducting wires take the place of the pipe. As the cross-sectional area of the wire increases, so does the amount of electric current (number of electrons) that can flow through it.



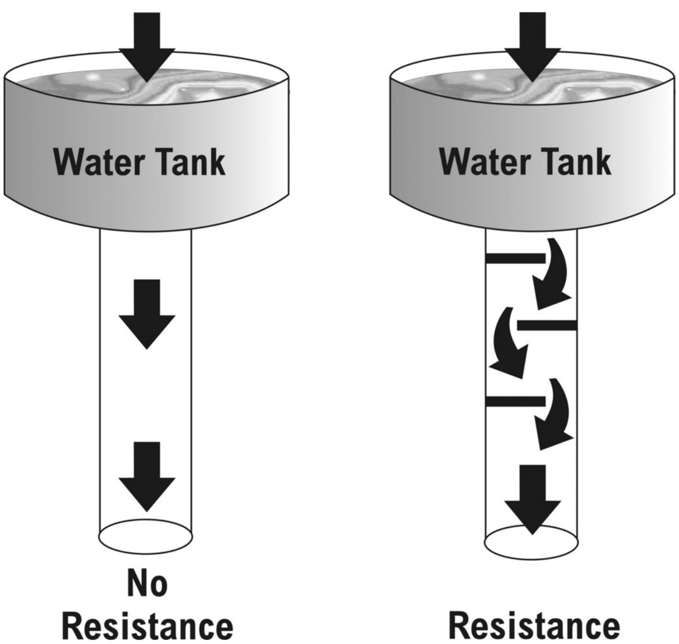
Resistance

Resistance (R) is a property that slows the flow of electrons. Using the water analogy, resistance is anything that slows water flow, a smaller pipe or fins on the inside of a pipe.

In electrical terms, the resistance of a conducting wire depends on the metal the wire is made of and its diameter. Copper, aluminum, and silver—metals used in conducting wires—have different resistance.

Resistance is measured in units called **ohms (Ω)**. There are devices called **resistors**, with set resistances, that can be placed in circuits to reduce or control the current flow.

Any device placed in a circuit to do work is called a **load**. The lightbulb in a flashlight is a load. A television plugged into a wall outlet is also a load. Every load has built-in resistance.



Ohm's Law

George Ohm, a German physicist, discovered that in many materials, especially metals, the current that flows through a material is proportional to the voltage.

In the substances he tested, he found that if he doubled the voltage, the current also doubled. If he reduced the voltage by half, the current dropped by half. The resistance of the material remained the same.

This relationship is called **Ohm's Law**, and can be written in a simple formula. If you know any two of the measurements, you can calculate the third using the following formula:

voltage = current x resistance

$V = I \times R$ or $V = A \times \Omega$

Electrical Power

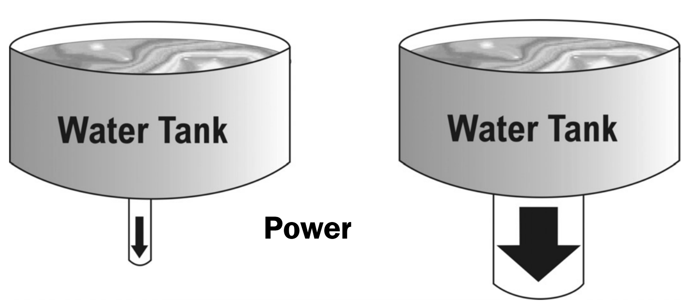
Power (P) is a measure of the rate of doing work or the rate at which energy is converted. Electrical power is the rate at which electricity is produced or consumed. Using the water analogy, electric power is the combination of the water pressure (voltage) and the rate of flow (current) that results in the ability to do work.

A large pipe carries more water (current) than a small pipe. Water at a height of 10 meters has much greater force (voltage) than at a height of one meter. The power of water flowing through a 1-centimeter pipe from a height of one meter is much less than water through a 10-centimeter pipe from 10 meters.

Electrical power is defined as the amount of electric current flowing due to an applied voltage. It is the amount of electricity required to start or operate a load for one second. Electrical power is measured in **watts (W)**. The formula is:

power = voltage x current

$P = V \times I$ or $W = V \times A$



Electrical Energy

Electrical energy introduces the concept of time to electrical power. In the water analogy, it would be the amount of water falling through the pipe over a period of time, such as an hour. When we talk about using power over time, we are talking about using energy. Using our water example, we could look at how much work could be done by the water in the time that it takes for the tank to empty.

The electrical energy that an appliance or device consumes can be determined only if you know how long (time) it consumes electrical power at a specific rate (power).

To find the amount of energy consumed, you multiply the rate of energy consumption (measured in watts) by the amount of time (measured in hours) that it is being consumed. Electrical energy is measured in **watt-hours (Wh)**.

Energy (E) = Power (P) x Time (t)

E = P x t or E = W x h = Wh

Another way to think about power and energy is with an analogy to traveling. If a person travels in a car at a rate of 40 miles per hour (mph), to find the total distance traveled, you would multiply the rate of travel by the amount of time you traveled at that rate.

If a car travels for 1 hour at 40 miles per hour, it would travel 40 miles.

Distance = 40 mph x 1 hour = 40 miles

If a car travels for 3 hours at 40 miles per hour, it would travel 120 miles.

Distance = 40 mph x 3 hours = 120 miles

When we look at power, we are talking about the rate that electrical energy is being produced or consumed. Energy is analogous to the total distance traveled.

A person wouldn't say he took a 40-mile per hour trip because that is the rate. The person would say he took a 40-mile trip or a 120-mile trip. Just as the total distance is calculated by multiplying miles per hour by time, the amount of energy is calculated by multiplying power (work/time) by time.

The same applies with electrical power. You would not say you used 100 watts of light energy to read your book, because 100 watts represents the rate you used energy, not the total energy used. The amount of energy used would be calculated by multiplying the rate by the amount of time you read.

If you read for 5 hours with a 100-W bulb, for example, you would use the formula as follows:

Energy = Power x Time (E = P x t)

Energy = 100 W x 5 hour = 500 Wh

One watt-hour is a very small amount of electrical energy. Usually, we measure electrical power in larger units called **kilowatt-hours (kWh)** or 1,000 watt-hours. (kilo = thousand). A kilowatt-hour is the unit that utilities use when billing most customers. The average cost of a kilowatt-hour of electricity for residential customers in the U.S. is about $0.11.

To calculate the cost of reading with a 100-W bulb for five (5) hours, you would change the watt-hours into kilowatt-hours, then multiply the kilowatt-hours used by the cost per kilowatt-hour, as shown below:

500 Wh divided by 1,000 = 0.5 kWh

0.5 kWh x $0.11/kWh = $0.055

It would cost about five and a half cents to read for five hours with a 100-W bulb.

REVIEW QUESTIONS

1. Identify and explain the nuclear reaction in the sun that produces radiant energy.

2. Define renewable energy. Explain why solar energy is considered renewable.

3. Explain why a car parked in the sun becomes hot inside.

4. Distinguish between passive and active solar space heating.

5. Why is a solar cell called a PV cell? What does the word photovoltaic mean?

6. Explain the conversion efficiency of a PV cell. How efficient are PV cells today?

7. Explain briefly how a PV cell converts radiant energy into electricity.

8. Do PV modules produce AC or DC current?

   Which type of current do most appliances use?

   What device converts DC to AC current?

9. Define the following electrical measures and the unit of measurement for each.

   voltage:

   current:

   resistance:

   power:

10. What is the average cost of a kilowatt-hour of electricity for U.S. residential customers?

Calculation of Power

Power (P) is a measure of the rate of doing work or the rate at which energy is converted. Electrical power is defined as the amount of electric current (I) flowing due to an applied voltage (V). Electrical power is measured in watts (W), current in amperes (A), and voltage in volts (V):

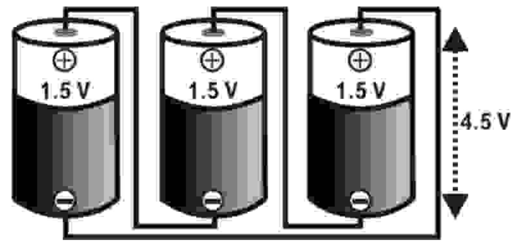
$$\text{Power} = \text{Current} \times \text{Voltage}$$
$$P = I \times V$$
$$\text{Watts (W)} = \text{Amps (A)} \times \text{Volts (V)}$$

Series Circuits

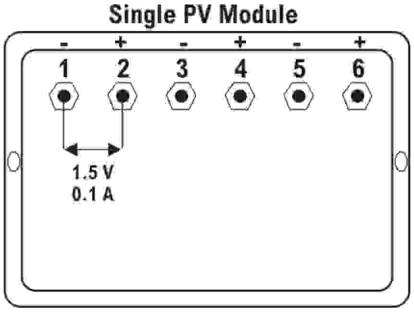
In series circuits, the current remains constant while the voltage changes. To calculate total voltage, add the individual voltages together:

$$I_{total} = I_1 = I_2 = I_3$$

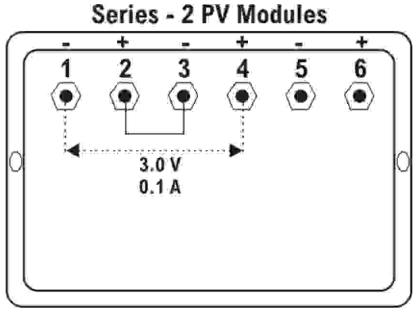
$$V_{total} = V_1 + V_2 + V_3$$



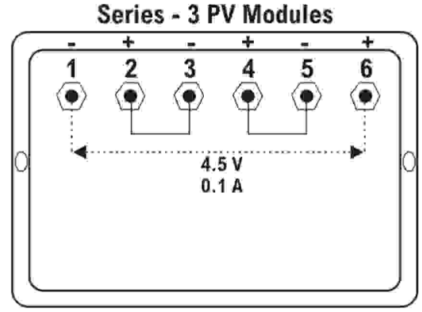
Single PV Module



Series - 2 PV Modules



Series - 3 PV Modules

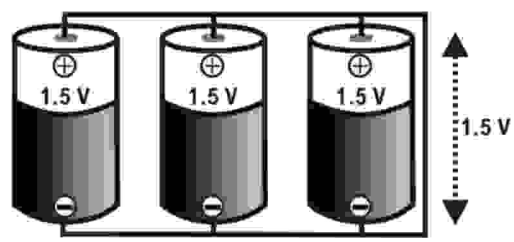


Parallel Circuits

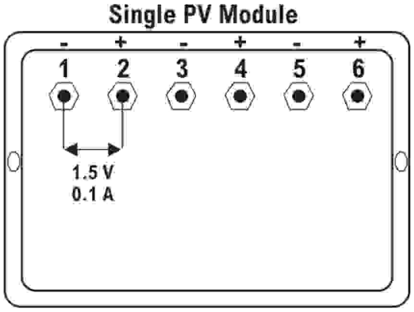
In parallel circuits, the voltage remains constant while the current changes. To calculate total current, add the individual currents together:

$$I_{total} = I_1 + I_2 + I_3$$

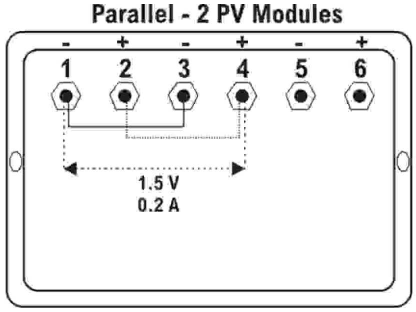
$$V_{total} = V_1 = V_2 = V_3$$



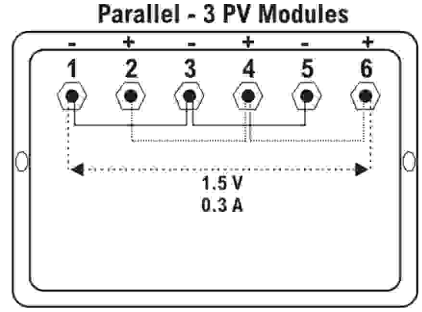
Single PV Module



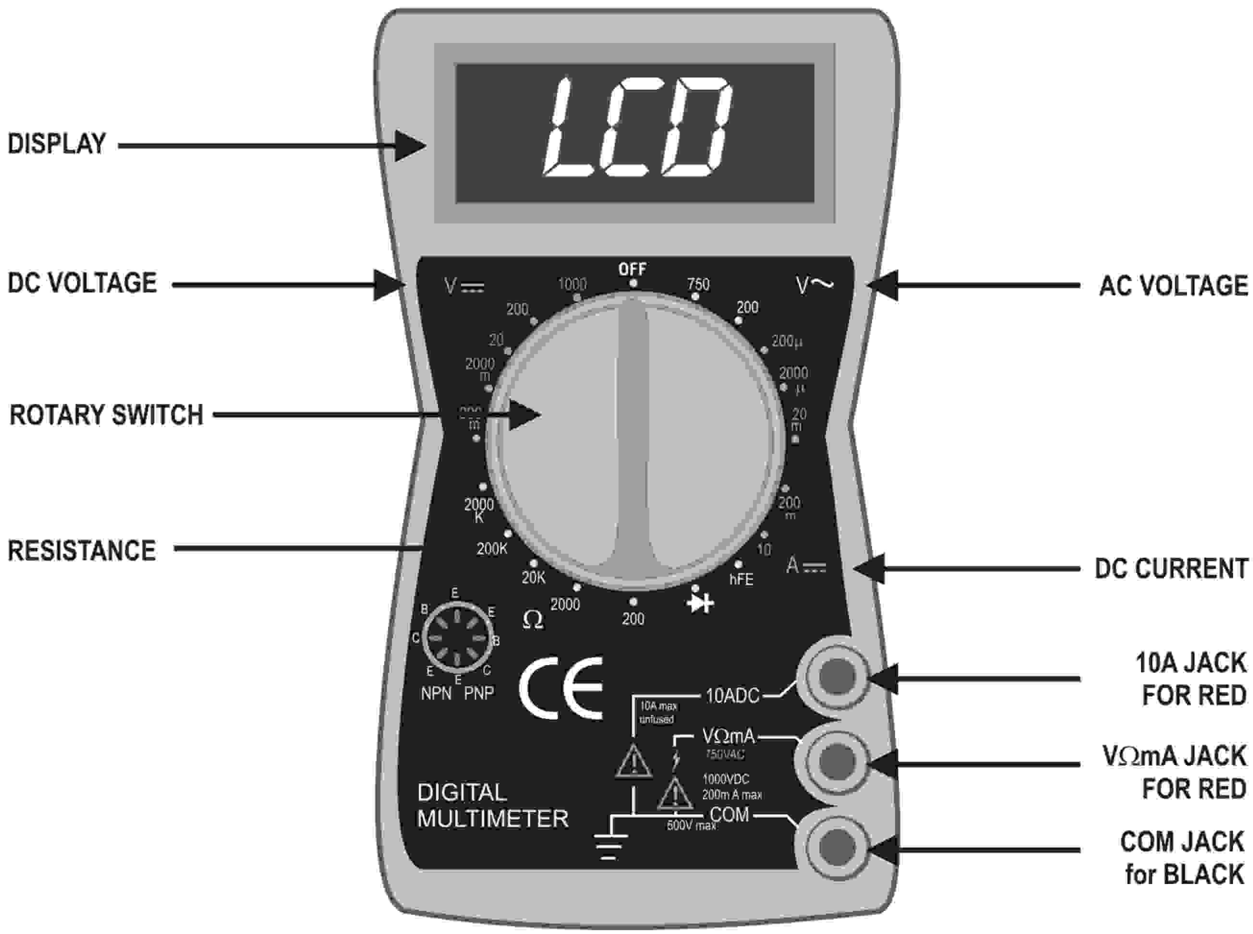
Parallel - 2 PV Modules



Parallel - 3 PV Modules



MULTIMETER



DC Voltage: Connect RED lead to VΩmA socket and BLACK to COM.
Set SWITCH to highest setting on DC VOLTAGE scale (1000).
Connect leads to the device to be tested using the alligator clips provided.
Adjust SWITCH to lower settings until a satisfactory reading is obtained.
With solar panels, usually the 20 setting provides the best reading.

DC Current: Connect RED lead to VΩmA connector and BLACK to COM.
Set SWITCH to 10 ADC setting.
Connect leads to the device to be tested using the alligator clips provided.

Note: The reading indicates DC AMPS; a reading of 0.25 amps equals 250 ma (milliamps).

YOUR MULTIMETER MIGHT BE SLIGHTLY DIFFERENT FROM THE ONE SHOWN.

BEFORE USING THE MULTIMETER

READ THE OPERATOR'S INSTRUCTION MANUAL INCLUDED IN THE BOX FOR SAFETY INFORMATION AND COMPLETE OPERATING INSTRUCTIONS.

SOLAR 1: Do Similar PV Cells Produce Similar Electrical Output?

HYPOTHESIS:

MATERIALS: PV panel with three PV modules, each with three PV cells
multimeter

PROCEDURE:

1. Measure the current and voltage of each PV module under identical external conditions.
2. Record the results below and compare.

RESULTS:

Left PV Module Output: _____ A x _____ V = _____ W

Center PV Module Output: _____ A x _____ V = _____ W

Right PV Module Output: _____ A x _____ V = _____ W

CONCLUSION:

SOLAR 2: How Does Light Intensity Affect the Electrical Output of a PV Cell?

HYPOTHESIS:

MATERIALS:

PROCEDURE:

RESULTS:

CONCLUSION:

CHALLENGES:

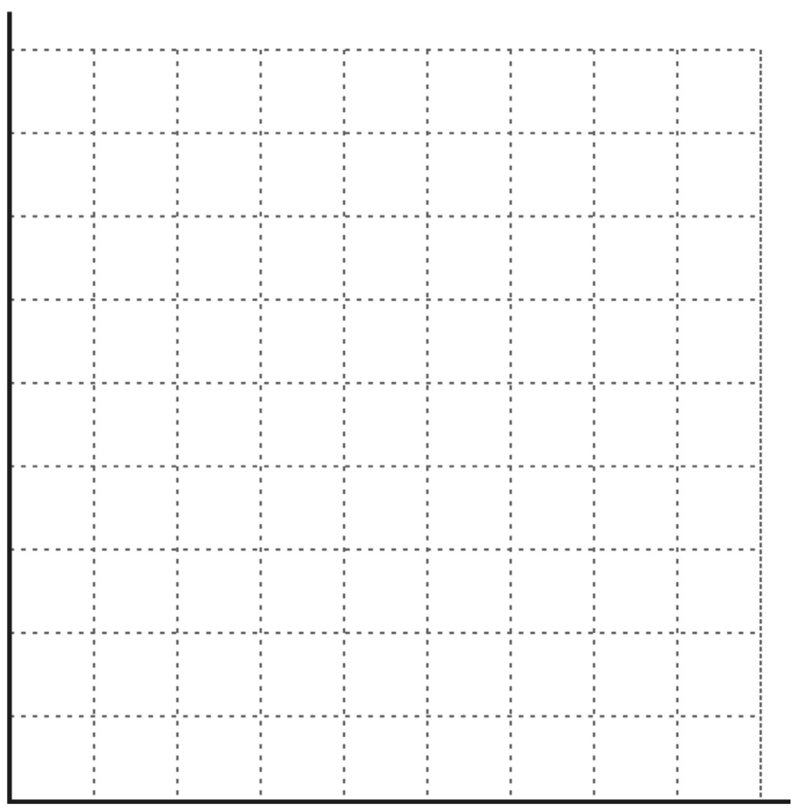
SOLAR 3: How Does the Angle of a PV Cell to a Light Source Affect the Electrical Output?

HYPOTHESIS:

MATERIALS:

PROCEDURE:

RESULTS (Graph the results):



CONCLUSION:

CHALLENGES:

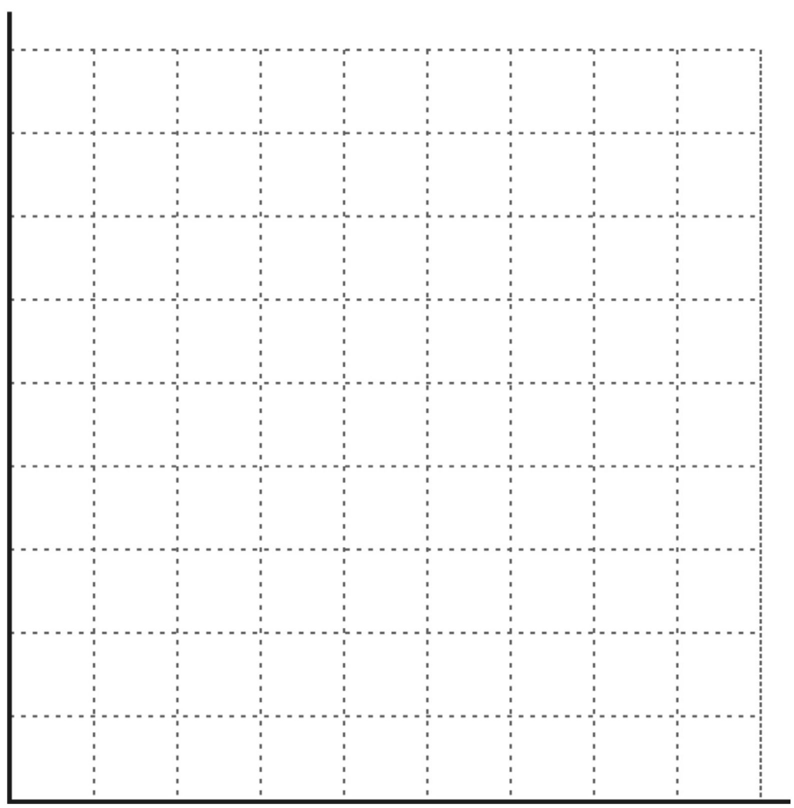
SOLAR 4: How Does the Distance from a Light Source Affect the Electrical Output of a PV Cell?

HYPOTHESIS:

MATERIALS:

PROCEDURE:

RESULTS (Graph the results):



CONCLUSION:

CHALLENGES:

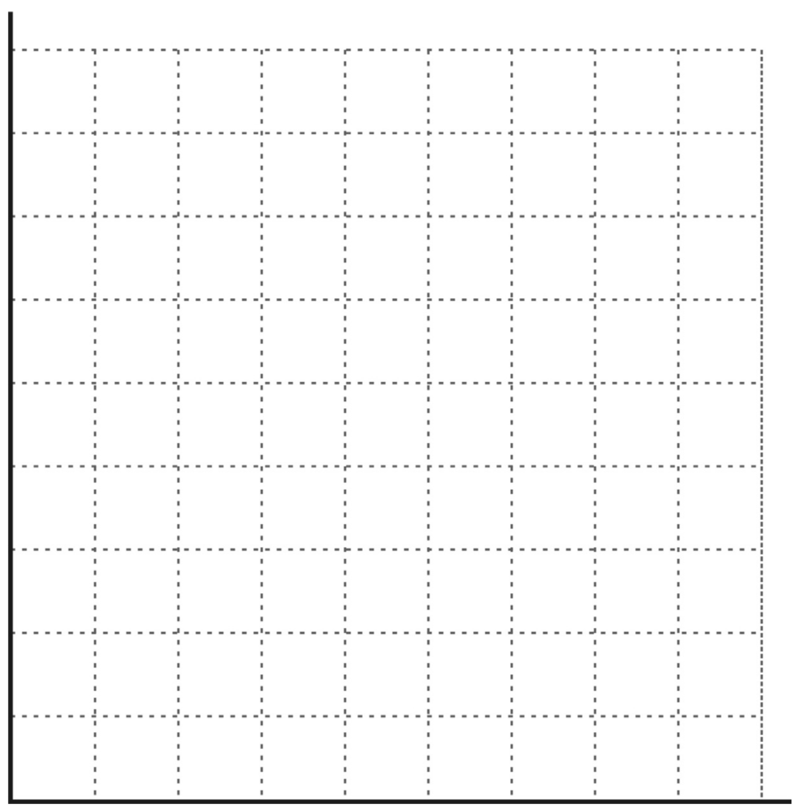
SOLAR 5: How Does Placing Part of a PV Cell in Shadow Affect Its Electrical Output?

HYPOTHESIS:

MATERIALS:

PROCEDURE:

RESULTS (Graph the results):



CONCLUSION:

CHALLENGES:

SOLAR 6: How Does the Color of the Light Affect the Electrical Output of a PV Cell?

HYPOTHESIS:

MATERIALS:

PROCEDURE:

RESULTS:

CONCLUSION:

CHALLENGES:

SOLAR 7: How Does Concentrating the Light from a Light Source Affect the Electrical Output of a PV Cell?

HYPOTHESIS:

MATERIALS:

PROCEDURE:

RESULTS:

CONCLUSION:

CHALLENGES:

SOLAR 8: How Does Air Temperature Affect the Electrical Output of a PV Cell?

HYPOTHESIS:

MATERIALS:

PROCEDURE:

RESULTS:

CONCLUSION:

CHALLENGES:

SOLAR 9: How Does Combining PV Cells in Parallel Affect the Electrical Output of the PV Panel?

HYPOTHESIS:

MATERIALS:

PROCEDURE:

RESULTS:

CONCLUSION:

CHALLENGES:

SOLAR 10: How Does Combining PV Cells in Series Affect the Electrical Output of the PV Panel?

HYPOTHESIS:

MATERIALS:

PROCEDURE:

RESULTS:

CONCLUSION:

CHALLENGES:

EXTENSION 1: To investigate the effects of changes in current and voltage on the operation of an electrical device (load).

HYPOTHESES: Read the procedure and record what you think the effects will be.

MATERIALS: 2 PV panels, 2 fan motors, 2 multimeters

PROCEDURE: Assemble 2 PV panel stands and 2 fan stands. Connect each PV panel to a fan.

Use one PV panel and fan to measure and observe changes in voltage and current with a single module, two modules, and three modules connected in SERIES.

Use one PV panel and fan to measure and observe changes in voltage and current with a single module, two modules, and three modules connected in PARALLEL.

DATA: Record your data and observations in the table below. Calculate power (watts).

Circuit Type	# Modules	Voltage	Current	Power	Observations
Series	1				
Series	2				
Series	3				
Parallel	1				
Parallel	2				
Parallel	3				

CONCLUSIONS:

What effects do changes in voltage and current have on fan performance?

What effects were observed when more than one module was used?

What was the difference in fan performance between series and parallel circuits?

CHALLENGES:

EXTENSION 2: To investigate the effects of adding multiple loads to different circuits.

HYPOTHESES: Read the procedure and record what you think the effects will be.

MATERIALS: 2 PV panels, 3 fan motors, 2 multimeters

PROCEDURE: Assemble the PV panel stand and fan stands.

Connect the three PV modules in SERIES on one PV panel and the three modules in PARALLEL on the second PV panel.

Measure and observe changes in voltage, current and performance of fans with a single fan, two fans, and three fans connected in SERIES to both PV panels.

Measure and observe changes in voltage, current and performance of fans with a single fan, two fans, and three fans connected in PARALLEL to both PV panels.

DATA: Record your data and observations in the table below. Calculate power (watts).

Circuit Type PV Panel	Number of Fans	Circuit Type Fans	Voltage	Current	Power	Observations
Series	1					
Series	2	Series				
Series	3	Series				
Series	2	Parallel				
Series	3	Parallel				
Parallel	1					
Parallel	2	Series				
Parallel	3	Series				
Parallel	2	Parallel				
Parallel	3	Parallel				

CONCLUSIONS:

Is voltage or current more important to the performance of electrical devices?

Give examples of loads in parallel and series circuits that you have used at home.

What might happen if too many loads are drawing power in your classroom?

CHALLENGES:

EXTENSION 3: To investigate the effects of using different light sources.

HYPOTHESIS:

MATERIALS: 1 solar panel, 1 multimeter, 1 music box, various light sources

PROCEDURE: Design a procedure to compare the output of the PV panel using natural sunlight and a variety of artificial light sources (incandescent, fluorescent, halogen).

DATA: Record your data and observations.

CONCLUSIONS:

CHALLENGES:

DESIGN YOUR OWN INVESTIGATION USING THE LIGHT BULB IN THE KIT:

HYPOTHESIS:

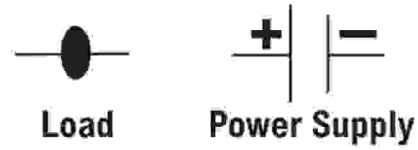
MATERIALS:

PROCEDURE:

RESULTS:

CONCLUSION:

CIRCUIT REVIEW: **Draw the wiring diagrams for the circuits in the boxes using the symbols below.**



2 Power Supplies in Series
2 Loads in Series

2 Power Supplies in Parallel
2 Loads in Parallel

3 Power Supplies in Parallel
3 Loads in Series

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Michigan Energy Office
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Mississippi Development Authority–Energy Division
Montana Energy Education Council
Narragansett Electric – A National Grid Company
NASA Educator Resource Center–WV
National Alternative Fuels Training Center–West Virginia University
National Association of State Energy Officials
National Association of State Universities and Land Grant Colleges
National Hydropower Association
National Ocean Industries Association
National Renewable Energy Laboratory
Nebraska Public Power District
New Jersey Department of Environmental Protection
New York Power Authority
New Mexico Oil Corporation
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